SSD-TDR-63-233

REPORT NO.
TDR-169(3511)TN-5

Launch Vehicle Performance Requirements for Rendezvous with Satellites in 200 Nautical Mile Circular Polar Orbits

20 SEPTEMBER 1963

Prepared by G. L. COATES

Prepared for COMMANDER SPACE SYSTEMS DIVISION

UNITED STATES AIR FORCE

Inglewood, California

SYSTEMS RESEARCH AND PLANNING DIVISION AEROSPACE CORPORATION
CONTRACT NO. AF 04(695)-169

SSD-TDR-63-233

Report No.
TDR-169(3511)TN-5

LAUNCH VEHICLE PERFORMANCE REQUIREMENTS FOR RENDEZVOUS WITH SATELLITES IN 200-NAUTICAL MILE CIRCULAR POLAR ORBITS

G. L. Coates

20 September 1963

Contract No. AF04(695)-169

AEROSPACE CORPORATION
2400 East El Segundo Boulevard
El Segundo, California

Prepared for

COMMANDER SPACE SYSTEMS DIVISION
UNITED STATES AIR FORCE
Inglewood, California

SSD-TDR-63-233

Report No.
TDR-169(3511)TN-5

LAUNCH VEHICLE PERFORMANCE REQUIREMENTS FOR RENDEZVOUS WITH SATELLITES IN 200-NAUTICAL MILE CIRCULAR POLAR ORBITS

20 September 1963

Prepared by G. L. Coates
G. L. Coates

Approved by L. J. Kulakowski
L. J. Kulakowski, Associate
Head, Performance Analysis
Department

AEROSPACE CORPORATION
2400 East El Segundo Boulevard
El Segundo, California

ABSTRACT

This report presents a detailed analysis of direct ascent rendezvous with polar orbits, illustrating quantitatively the effects of range angle, launch azimuth, and satellite epoch on the ascent trajectory and the performance required of the launch vehicle.

The total ideal velocity capability required of the launch vehicle to achieve gross rendezvous with satellites in 200-nautical mile circular polar orbits was determined as a function of the launch azimuth, the relative epoch of the orbit, and the pass on which rendezvous takes place. A direct ascent launch vehicle trajectory was assumed. Precision flight simulation techniques were used throughout except for the assumption of an impulsive adaptation maneuver. Launch window effects were not included; rather, the study was concerned with the selection and characteristics of nominal trajectories.

CONTENTS

ILLUSTRATIONS

I. INTRODUCTION

The analysis of the launch vehicle performance required for rendezvous in general can be described as a problem of mapping a multidimensional surface and of locating minimum points and certain contour lines. The dependent variable of primary interest is the performance (total ideal velocity capability) required of the launch vehicle.

The role of the launch vehicle is considered to be that of conveying the rendezvous vehicle from the launch pad to a point near the satellite and of providing at arrival a specified small velocity vector relative to the satellite. Typically, the task of the launch vehicle might end with the rendezvous vehicle 50 miles ahead of the satellite and drifting toward the satellite at a relative velocity of 500 ft/sec. The primary question of interest is how much ideal velocity is required of the launch vehicle to achieve this end. This is equivalent to asking how much payload a given vehicle can carry on this mission, how much propellant it would consume with a given payload, or how much velocity change capability it would have left after completing this task.

The variables which are involved in the problem include the selection of the launch vehicle and the launch site, the elements of the satellite orbit, the choice of the pass on which rendezvous takes place, and a large number of ascent trajectory variables.

The launch vehicle selected for this study was an Atlas D/Agena D as described in Reference 1. The vehicles were assumed to be launched from AMR. The following describe the satellite orbit and the ascent trajectory parameters, respectively, which were considered in the study.

A. Satellite Orbits

There are, in general, six quantities involved in the description of a satellite orbit. The quantities conventionally used are:

1. Semi-major axis
2. Eccentricity
3. Longitude of the ascending node
4. Argument of perigee
5. Inclination
6. Epoch

For this study, the eccentricity was assumed to be zero, which left the argument of perigee undefined. This gap was filled by arbitrarily (and conveniently) defining the argument of perigee as zero, i.e., by stating that perigee coincides with the ascending node. The semi-major axis could then be given in terms of the orbit altitude above a spherical earth; for ease of exposition this was done. The longitude of the ascending node and the epoch are of importance for rendezvous studies only in that together they determine the relative motion of the satellite and the launch site. These two elements can be combined for rendezvous study purposes by defining a relative epoch as follows. First, a reference point in space is defined as being the point of intersection of the launch site circle of latitude with the northbound side of the satellite orbit. A time scale is then defined in which time, t', is zero when the launch site passes through the reference point. In other words, $t' = 0$ when the launch site passes through the northbound half of the orbit plane.

The unit of time used in the t' scale is the nodal period of the orbit, i.e., the time interval between successive passages through the ascending node. Relative epoch, denoted by T', is then defined as the time of the most recent perigee passage in the t' scale. This endows the relative epoch with some useful properties. A given satellite will have many relative epochs which differ by 1.00. For example, $T' = 5.34$, 6.34, 7.34, or 8.34 all represent the same satellite. The number to the right of the decimal, together with the algebraic sign, identifies the satellite while the number to

the left of the decimal, together with the algebraic sign, identifies the pass on which the rendezvous takes place. (The zeroeth pass is the one during which the launch site passes through the reference point.)

For this study, the mathematical description of the orbit consisted of basic Keplerian equations with first order oblateness terms added whose effect is to alter the nodal period and to cause the line of nodes to regress at a constant rate.

In summary, the satellite orbit is assumed to be circular and perigee is defined as coinciding with the ascending node. The orbit specification is completed by giving values for the following parameters:

1. Altitude
2. Inclination
3. Relative epoch

The computer runs for this study were all for an altitude of 200 nautical miles. Data was obtained for inclinations ranging from 20 to 160 degrees in 10-degree increments. However, time has permitted the processing of only the polar orbit data, hence this report is confined to that case. The relative epoch was one of the dependent variables of the study.

B. Ascent Trajectory

The phase trajectory shape actually encompasses an n-dimensional realm of possible variations. For the purposes of this study, the ascent trajectory was assumed to be of the "direct ascent" variety. As such, the vehicle is launched, follows a conventional ascending powered flight pattern, cuts off thrust at the proper time and coasts until it reaches the satellite orbit. It then performs an "adaptation maneuver", i.e., it applies thrust in such a way that at the end of the maneuver its velocity vector is colinear with that of the satellite and 500 ft/sec less than that of the satellite. The flight is planned such that the relative position vector between the satellite and the

rendezvous vehicle is essentially zero at adaptation, i.e., the rendezvous vehicle and the satellite arrive at the adaptation point simultaneously. Thus, at the end of the adaptation maneuver the rendezvous vehicle is ready to begin its terminal rendezvous maneuvers and the launch vehicle task is completed. It may be noted that with direct ascent the launch site is usually not in the plane of the satellite orbit at launch and hence the adaptation maneuver usually includes a plane change (dog-leg).

It was assumed that during boost the vehicle would follow the pitch program given in Reference 1, multiplied by a constant which was one of the independent variables of the study. During the sustainer phase of flight and during the Agena first burn the vehicle was assumed to follow a constant pitch rate of 0.086 deg/sec. The specification of trajectory shape was then completed by requiring that rendezvous take place at apogee of the ascent trajectory; thus, thrust cutoff was signalled when the predicted apogee altitude equalled 200 nautical miles.

The trajectories were computed by an IBM 7090 using the N-Stage Program, a precision rotating-oblate-earth simulation. The method of using the program in this study and the equations for the rendezvous calculations are described in Reference 2. In brief, the procedure is to specify a launch azimuth and a pitch multiplier, fly the trajectory to apogee, and then evaluate performance, relative epoch, relative launch time, etc., for satellites in each of a series of orbit inclinations. The process is repeated for a systematically varied family of values of launch azimuth and pitch multipliers. The procedure yields data points whose accuracy is limited only by the assumption that the adaptation maneuver is performed impulsively.

II. RESULTS

As mentioned earlier, the study results presented here are for Atlas D/ Agena D vehicles launched from AMR to achieve rendezvous with satellites in 200 nautical mile circular polar orbits.

The independent variables were:

1. Launch azimuth
2. Pitch multiplier

The dependent variables were:

1. Range angle from launch to adaptation in both earth-fixed and space-fixed coordinates
2. Latitude and longitude of the adaptation point
3. Magnitude and direction of the rendezvous vehicle velocity vector just prior to adaptation
4. Dog-leg angle; i.e., the angle between the ascent trajectory plane and the satellite orbit
5. Magnitude of the adaptation maneuver velocity impulse
6. Ideal velocity required for ascent
7. Total ideal velocity required
8. Velocity capability remaining after adaptation
9. Geographic longitude of the ascending node at launch and at adaptation, difference in longitude between the launch site at launch and the northbound side of the orbit plane, and other longitude data
10. Relative launch time
11. Relative time at adaptation
12. Flight time
13. Relative epoch

The main variables of interest are the launch azimuth, the range angle (space-fixed), the dog-leg angle, the total ideal velocity required, and the relative epoch. The primary output of the study presents the relationships between those variables as plots of velocity required, range angle, and dog-leg angle versus relative epoch with launch azimuth as a parameter. These plots are presented in Figures 1 through 6. Data on the other variables is available in tabular form and could be similarly plotted; however, this has not yet been done.

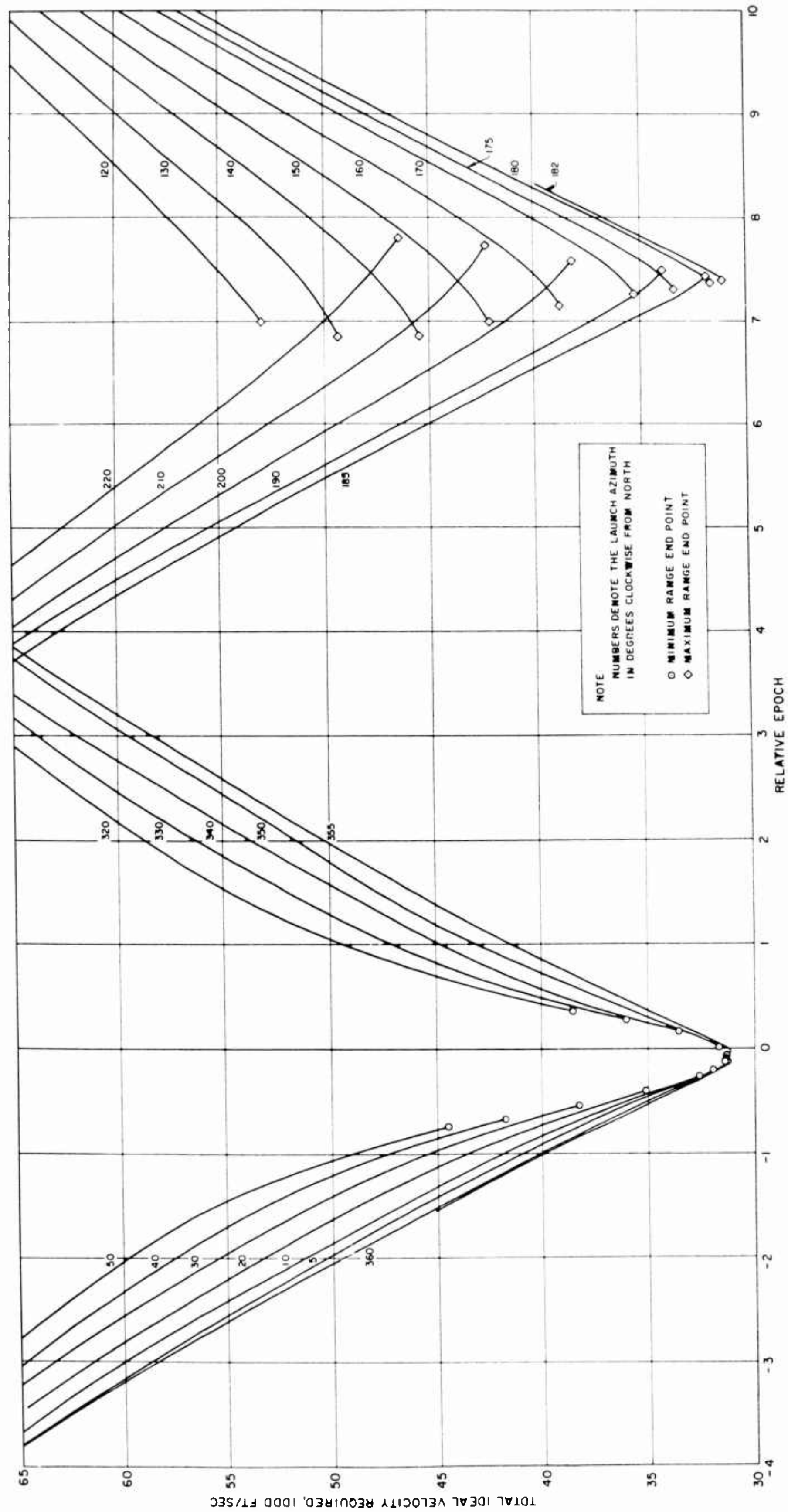


Figure 1. Total Ideal Velocity Required (Atlas/Agena) Versus Relative Epoch with the Satellite Northbound at Adaptation.

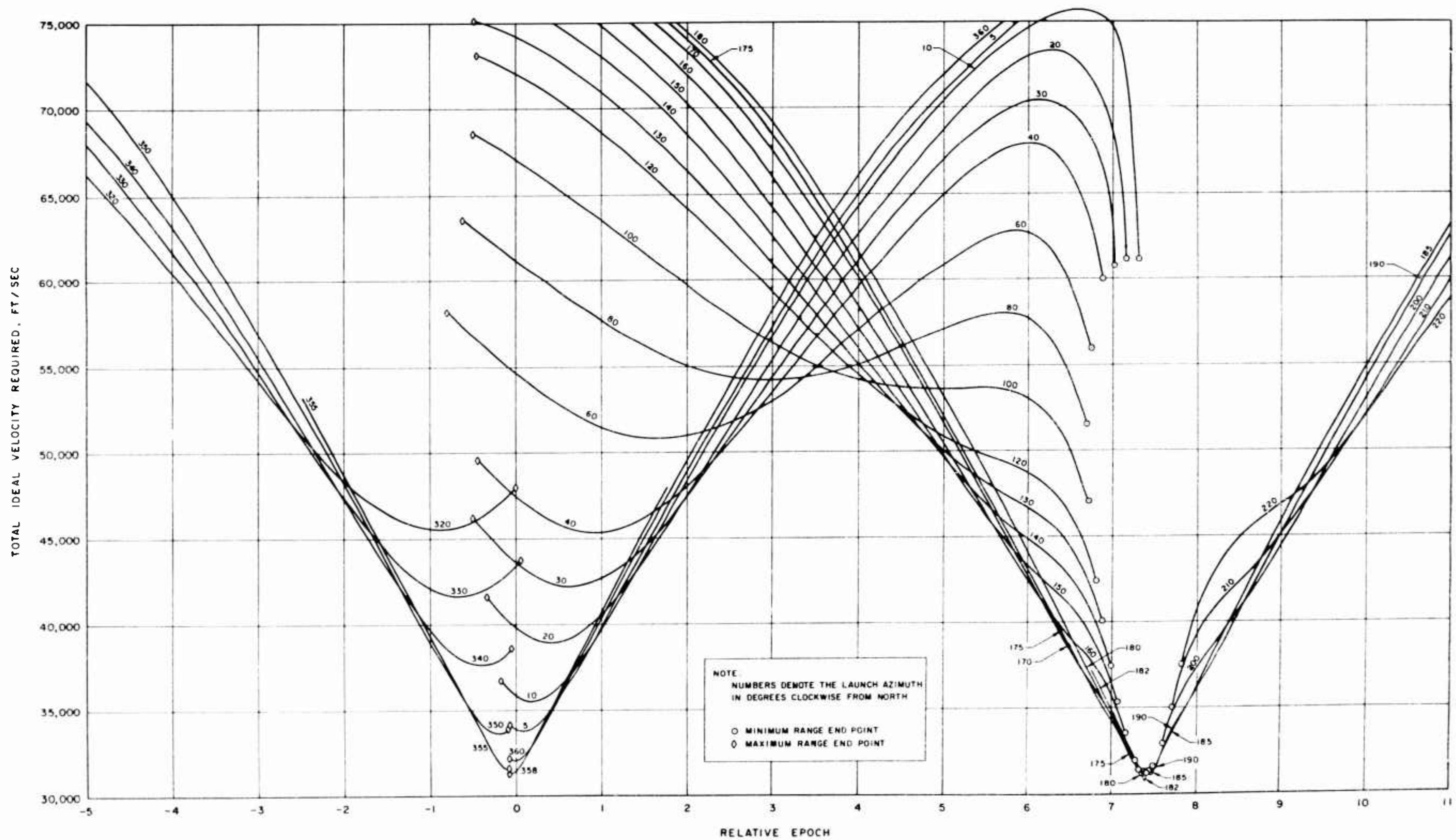


Figure 2. Total Ideal Velocity Required (Atlas/Agena) Versus Relative Epoch with the Satellite Southbound at Adaptation.

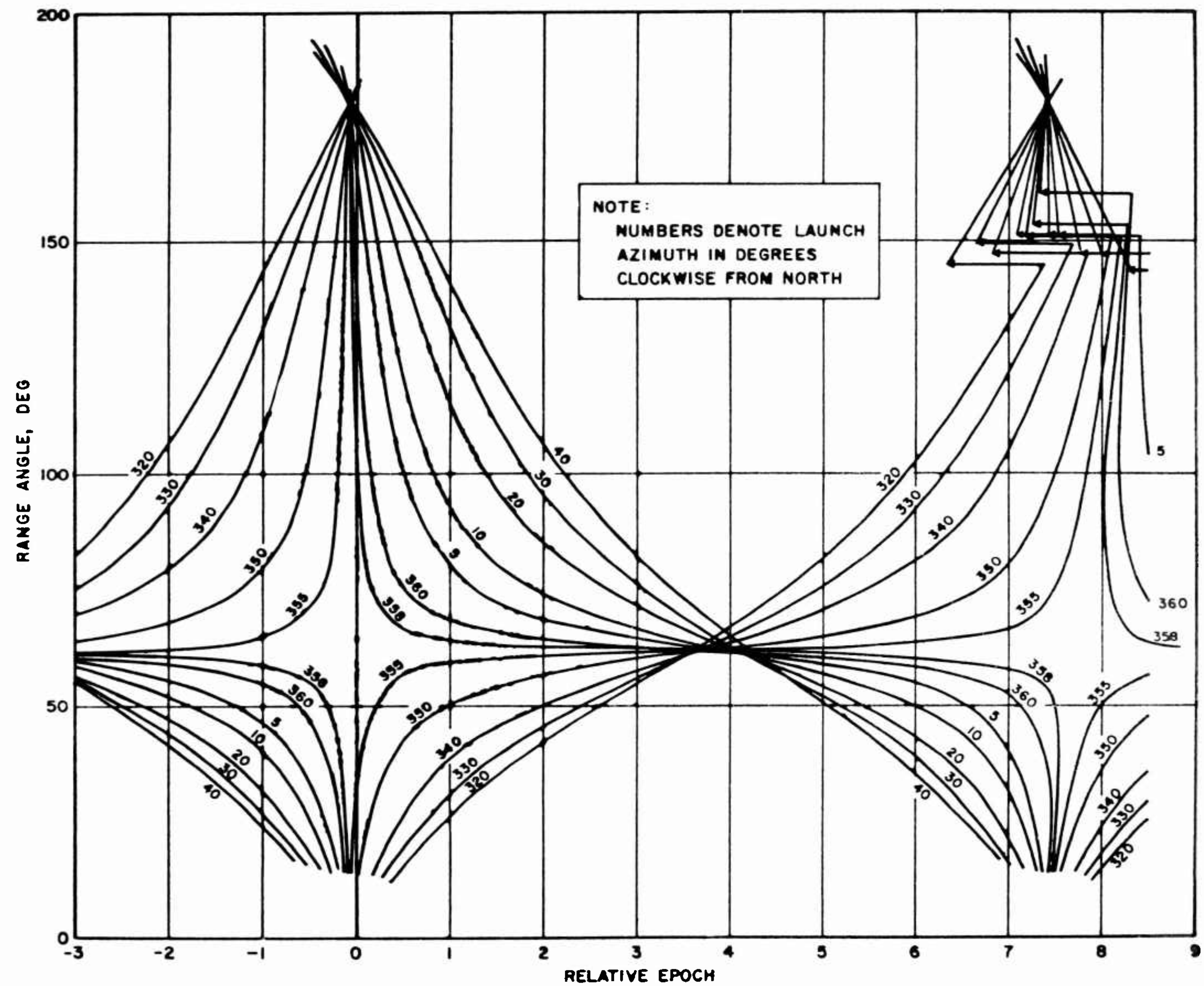


Figure 3. Space-Fixed Range Angle from Launch to Adaptation Versus Relative Epoch for Northerly Launch Azimuth.

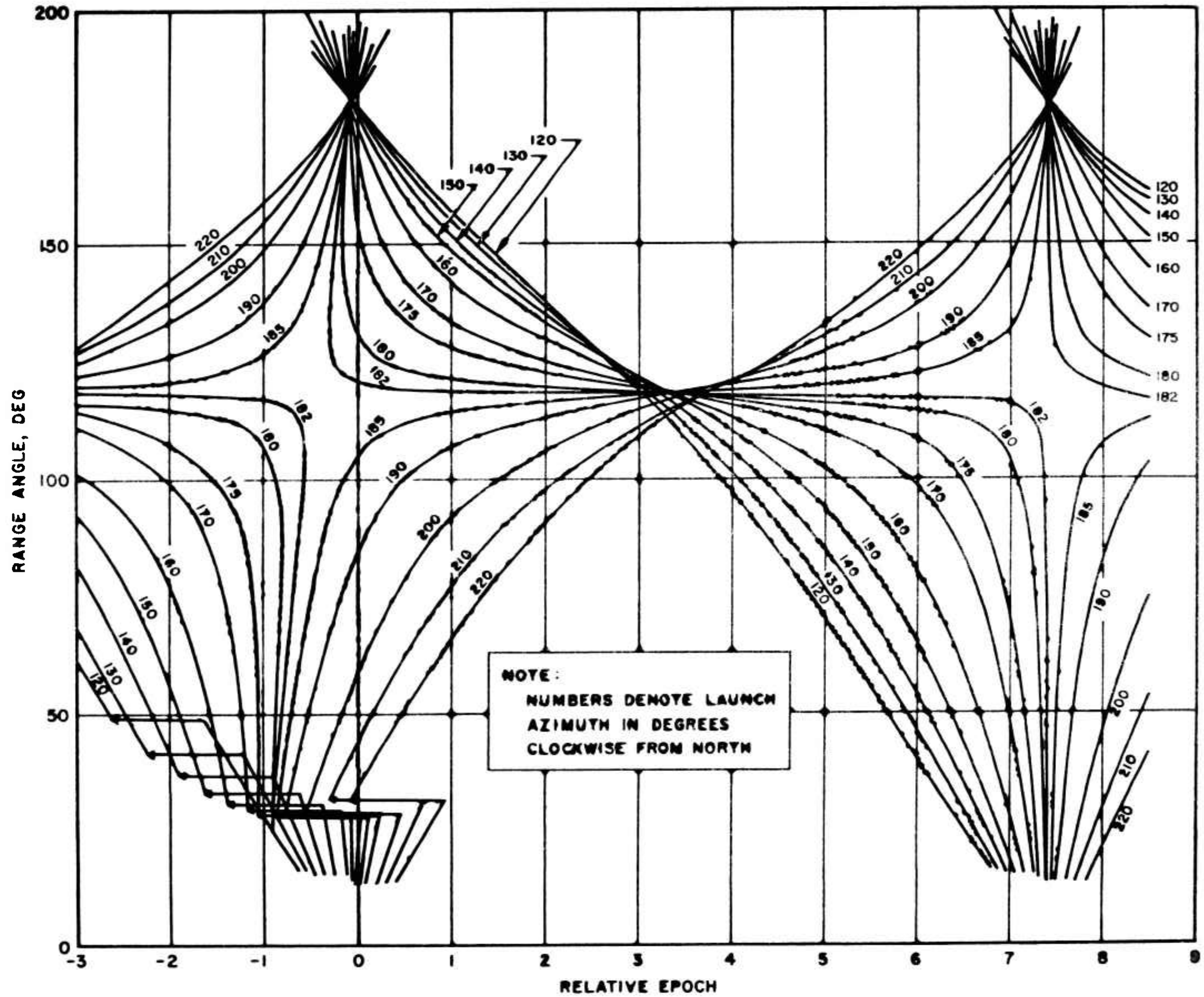


Figure 4. Space-Fixed Range Angle from Launch to Adaptation Versus Relative Epoch for Southerly Launch Azimuth.

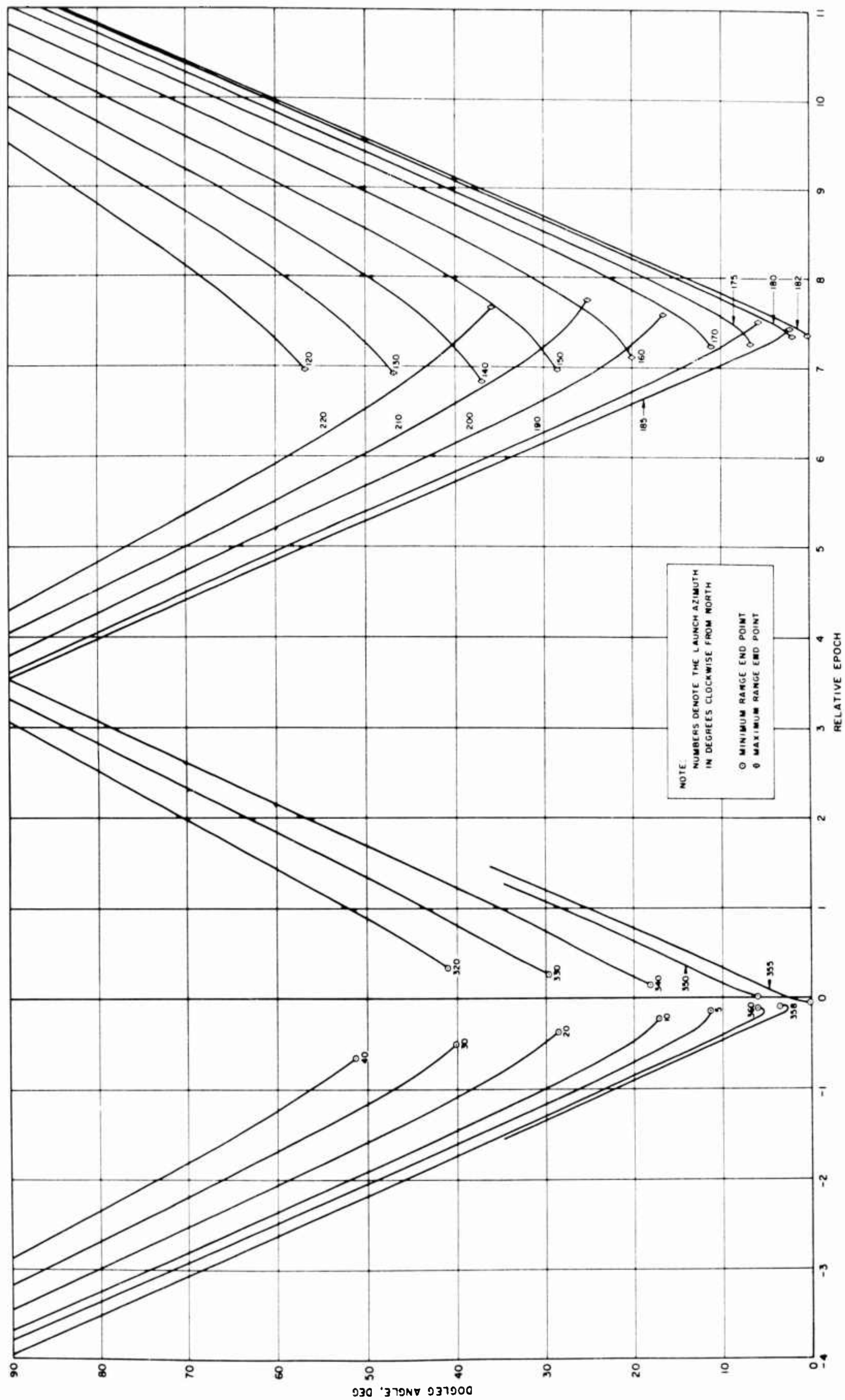


Figure 5. Dog-Leg Angle Versus Relative Epoch with the Satellite Northbound at Adaptation.

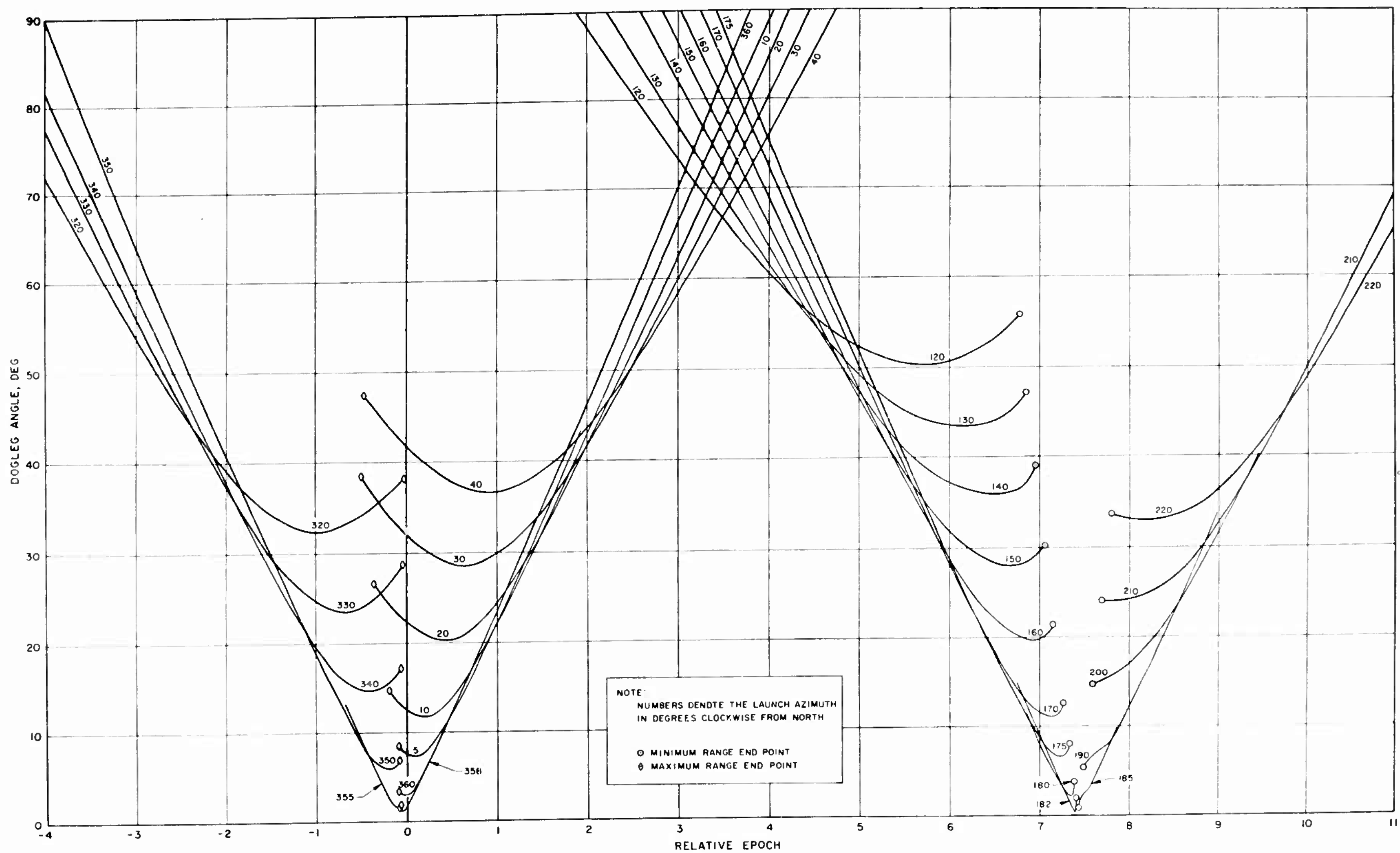


Figure 6. Dog-Leg Angle Versus Relative Epoch with the Satellite Southbound at Adaptation.

The results discussed in this section can be understood best by remembering that the procedure used was to:

1. Fly a trajectory from launch to apogee
2. Determine the elements of orbits at given inclinations passing through the apogee point
3. Determine the adaptation maneuver required for rendezvous with each of these orbits

There are, in general, two orbits of a given inclination passing through a given rendezvous point, one in which the satellite is northbound at rendezvous and one in which it is southbound.* Each trajectory, therefore, generates two data points for each inclination, and each set of trajectories generates two sets of curves for each inclination. Some of the curves are such that both northbound and southbound cases can be placed on a single sheet. Other curves are such that the northbound and southbound families overlap and hence must be plotted on separate sheets.

Figures 1 and 2 contain plots of total ideal velocity required versus relative epoch, with launch azimuth as the parameter, for the cases in which the satellite is northbound and southbound respectively at adaptation. As described earlier, each point on the relative epoch scale represents a particular satellite on a particular pass. A given satellite shows upon the scale at regular intervals at 1.0 (e.g., relative epoch at 5.34, 6.34, 7.34, etc., reflect one particular satellite). Thus, these two figures together present the complete relationship between the launch azimuth, the satellite epoch, the choice of the pass, and the required launch vehicle performance.

There is a strong correlation between launch time and relative epoch; thus, in general, as one moves to the right on these curves one is considering progressively later launch times. Relative epochs near zero correspond to

---

*This point is discussed more fully in Reference 2. For nonpolar orbits there is more to it than these simple statements.

launches in or near the northbound side of the orbit plane, while the relative epochs near 7.4 correspond to launches a half day later, in or near the south-bound side of the orbit plane.

The curves are cyclic, repeating themselves at intervals of 15.6526, the number of revolutions made by a satellite in this orbit per day (between successive passages of the launch site through the northbound side of the orbit plane).

The additional symmetry afforded by the 90-degree inclination causes the lower envelope of the curves to approximately repeat itself each half day (at intervals of about 7.5 and 8.1); if the launch site were at the equator, this repetition would be almost exact at intervals of 7.83.

One immediate result obtainable from these figures is the coverage obtainable with a given available launch vehicle performance; i.e., the percentage of all possible satellites in 200 nautical mile circular polar orbits that will be "within reach" of the given system during a given period of time. For example, consider the time period of about one day shown in Figures 1 and 2 and suppose the launch vehicle has a capability of 33,000 ft/sec. The satellites represented by the portions of the curves below 33,000 ft/sec are then within reach of the vehicle. Reading from the graphs, satellites with relative epochs between -0.34 and +0.2 or between 7.14 and 7.66 can be handled by this vehicle. It follows from the definition of relative epoch that a span of relative epochs equal to 1.0 represents all possible satellites; hence, the two intervals of coverage above represent coverages of 54 and 52 per cent, respectively. Since the satellite of relative epoch -0.34 shows up again at relative epochs of 0.66, 1.66, ..., 7.66 and the satellite of epoch 0.2 similarly shows up at 8.2, it turns out that these two areas of coverage complement each other perfectly, providing a total span of coverage at 1.06 for this one day. A total of 48 per cent of the satellites could be reached only by launching near the northbound side of the orbit plane, 46 per cent could

only be reached by launching a half day later near the southbound side of the orbit plane, and 6 per cent could be reached on either opportunity.

More realistically, an operational system must be capable of handling much higher altitudes and hence would require an ideal velocity capability of at least 40, 000 ft/sec (this, incidentally, is approximately the amount needed for a lunar impact mission). The curves show that a vehicle with this capability could cover a span of relative epochs of 2. 15 by launching near the northbound side of the orbit plane and a span of 2. 13 by launching near the southbound side of the orbit plane. In round numbers, such a system could rendezvous with any satellite in a 200 nautical mile circular polar orbit on either of two consecutive passes, launching on either side of the earth.

The above discussions have tacitly assumed an absence of launch azimuth constraints. The imposition of such constraints of course simply eliminates part of the family of curves in these figures. For example, if one wishes to keep the nominal impact points of the booster and the sustainer off dry land, the launch azimuth must lie roughly between 40 and 120 degrees. Under this constraint, the launch vehicle would need a capability of 41, 700 ft/sec to provide any coverage at all and would need a capability of 46, 000 ft/sec to provide 100 per cent coverage during a one day interval. This is approaching the capability required for a one-way probe to Mars or Venus. One could use the data of Figures 1 and 2 to generate curves of capability required for 100 per cent coverage versus the upper bound on launch azimuth with the lower bound as a parameter and thus illustrate the trade-off. Alternatively, one could take a given available velocity capability and generate curves of the per cent coverage versus the upper bound with the lower bound as a parameter.

One last comment is in order regarding Figures 1 and 2. These are based upon the assumption of an impulsive adaptation maneuver. The ideal velocity used for ascent is between 20, 000 and 30, 000 ft/sec in all cases,

and near 30, 000 ft/sec in a great majority of the cases. Hence, the magnitude of the adaptation maneuver is roughly the total ideal velocity required minus 30, 000 ft/sec. For total ideal velocities less than, for instance, 45, 000 ft/sec the adaptation maneuver is less than 15, 000 ft/sec and has the effect of rotating a large velocity vector through an angle of 40 degrees or less. Under these circumstances, the assumption of an impulsive velocity change is acceptable. However, the assumption rapidly becomes untenable as the total ideal velocity requires increases to 60, 000 or 70, 000 ft/sec; hence, the top part of Figures 1 and 2 are of little more than academic interest, except that data points in this region help in constructing the curves through the regions of interest.

Figures 3 and 4 contain plots of the range angle (geocentric angle between the launch site at launch and the adaptation point) versus the relative epoch with launch azimuth as the parameter. Figure 3 covers the region of launch azimuths between 320 and 40 degrees, while Figure 4 covers azimuths between 120 and 220 degrees. These curves are of use primarily as a data source for cross plots; however, they do have certain features of interest. First, a jump discontinuity of 1. 0 in relative epoch occurs once in each curve. These discontinuities arise from the definition of relative epoch and mark the point where one pass ends and the next begins. It may be noted that they occur in regions of very large dog-leg angles and velocity requirements, i. e., in regions of little practical interest. These regions are off the top of the graph in Figures 1, 2, 5 and 6. Second, it is noted that the curves seem to pass through one of two common points at a range angle of 180 degrees, and that these two relative epochs seem to form rough lines of symmetry for the pattern. These two epochs correspond to cases where it is possible to launch directly in the plane of the satellite orbit and achieve rendezvous with a zero dog-leg angle, thus with a minimum ideal velocity required. It turns out in these cases that the launch time is a very weak function of range angle and launch azimuth; hence, for these two epochs, the launch site is essentially in

the plane of the orbit at launch regardless of the launch azimuth or range angle. Since both the satellite orbit and the ascent trajectories project on the celestial sphere approximately as great circles whose terminal intersection is the adaptation point, it follows that if the launch point is in the orbit plane either the two planes coincide or the range angle will be 180 degrees. There are second order effects present which will be discussed later, but the figures illustrate that, for this orbit at least, the preceding sentence describes the situation quite well. The same phenomenon has been observed for other orbit inclinations at this same altitude.

Figures 5 and 6 present plots of the dog-leg angle versus the relative epoch for cases where, at adaptation, the satellite is northbound and southbound, respectively. The strong similarity between these curves and those of Figures 1 and 2 immediately demonstrates that, as expected, dog-leg angle is the primary factor determining the ideal velocity required.

In order to better understand the trade-offs involved in rendezvous performance, it is instructive to choose a particular satellite and examine the variation in trajectory parameters as the launch azimuth and the choice of the pass are varied. Two satellites were selected for such examinations. The first is the satellite for which in-plane ascent is possible; it is examined on five consecutive passes beginning two passes prior to the in-plane launch pass. The relative epochs here are -2.068, -1.068, -0.068, +0.932, and +1.932. The second satellite is 180 degrees away from the first satellite. It is examined on two consecutive passes corresponding to launches roughly one-half period before and after the time when the launch site passes through the northbound side of the orbit plane. The relative epochs here are -0.568 and +0.432.

Figure 7 presents plots of the range angle, the dog-leg angle, and the total ideal velocity required versus the launch azimuth for the first satellite with relative epoch equal to -2.068. The primary effects shaping these curves

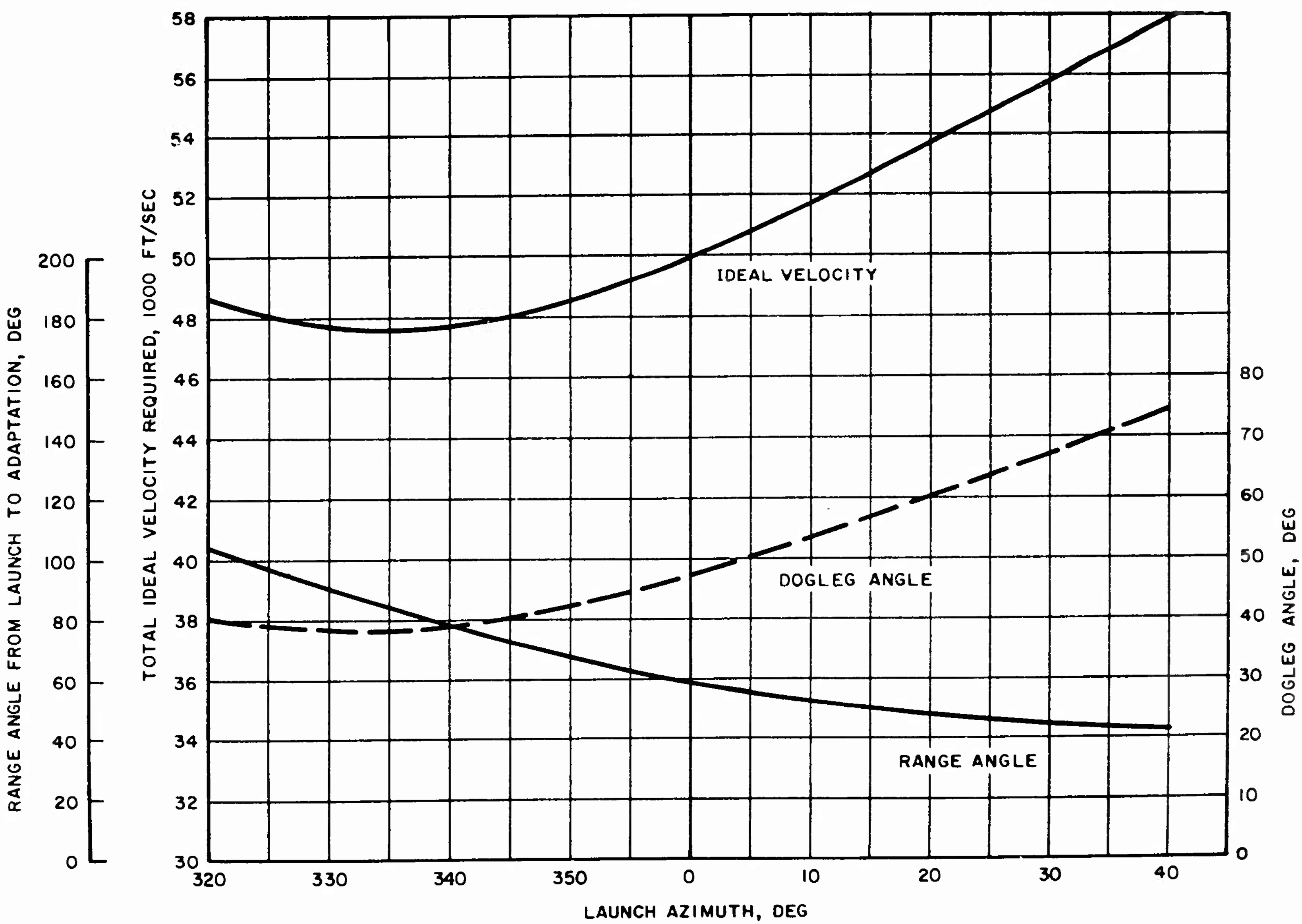
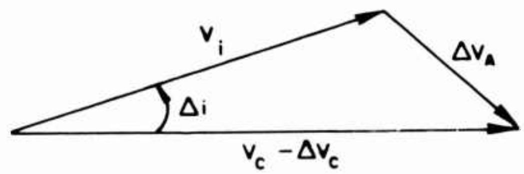


Figure 7. Performance with Relative Epoch = -2.068.

were brought out in Reference 3 which approximates the situation by neglecting the variation in flight time with launch azimuth and relative epoch and the feedback of this variation into the angle separating the launch site and the orbit plane at launch. In the case at hand, rendezvous could be achieved with an in-plane launch. Catching the same satellites two passes earlier would, by the logic of Reference 3, call for launching two passes earlier with an out-of-plane separation of 39.3 degrees. It follows further from Reference 3 that the minimum dog-leg angle would be equal to the out-of-plane separation and would be obtained with a range angle of 90 degrees. Inspection of Figure 7 shows that this is very nearly what actually happens. The minimum dog-leg angle is 38.5 degrees and is obtained with a range angle of essentially 90 degrees and an out-of-plane separation of 39.5 degrees. The difference between these two angles is due to earth rotation effects; i.e., the ascent trajectory is not actually a plane in inertial space but rather begins with a due east motion from the earth rotation. As the missile pitches over and thrusts toward the north, the path rapidly curves around toward the north and becomes approximately planar. The initial eastward motion produces the difference noted above between dog-leg angle and the out-of-plane separation at launch.

Again, the strong correlation between dog-leg angle and ideal velocity required is observed. Clearly, dog-leg angle does dominate the picture. However, close inspection of Figure 7 reveals that the minimum ideal velocity point, although close to the minimum dog-leg angle point, is not the same; it falls at a range angle of about 85 rather than 90 degrees. This may be understood by examining the velocity vector diagram used to compute the adaptation maneuver.



In this diagram, V_i is the inertial velocity of the rendezvous vehicle just prior to adaptation, ΔV_A is the adaptation maneuver, and $(V_c - \Delta V_c)$ is the required final velocity (orbital velocity minus the desired closing velocity between the satellite and the rendezvous vehicle). The total ideal velocity required is $V_i + \Delta V_A$ plus the velocity losses incurred during ascent. The total $V_i + \Delta V_A$ can be reduced either by reducing Δi or by reducing V_i. Since the first derivative of Δi with respect to range angle is essentially zero at a range angle of 90 degrees, a slight reduction in range angle does not perceptibly affect Δi. However, it does perceptibly reduce V_i, hence reducing the total $V_i + \Delta V_A$. This is partly offset by an increase in the losses, but the total effect is to shift the minimum velocity point from a range angle of 90 degrees to a somewhat smaller range angle. It also has the effect of significantly altering the slope of the ideal velocity curve from what it would be where only the dog-leg angle effect included. This is illustrated clearly in Figure 8, where the right-hand branch of the velocity curve (corresponding to progressively shorter range angles) has a much milder slope than the left-hand, long range angle, branch. This is illustrated further by comparing the ideal velocity versus epoch curves of Figure 2 with the dog-leg angle versus epoch curves of Figure 6. These two sets of curves have very similar shape except for epochs between 6 and 8. In this region one finds dog-leg angle curves breaking upward while the corresponding ideal velocity curves break downward. The end points of these curves in this region are minimum range points set by vehicle constraints; as one moves along one of these curves towards the end point one is moving towards progressively shorter range angles, hence smaller V_i's, hence smaller total ideal velocity required despite a somewhat increased dog-leg angle.

Figure 8 is similar to Figure 7; it presents performance data for the same satellite one pass later. The same effects are seen to be present.

Figure 9 presents the picture for the same satellite one pass later again. This is the pass for which in-plane launch is possible. As described earlier

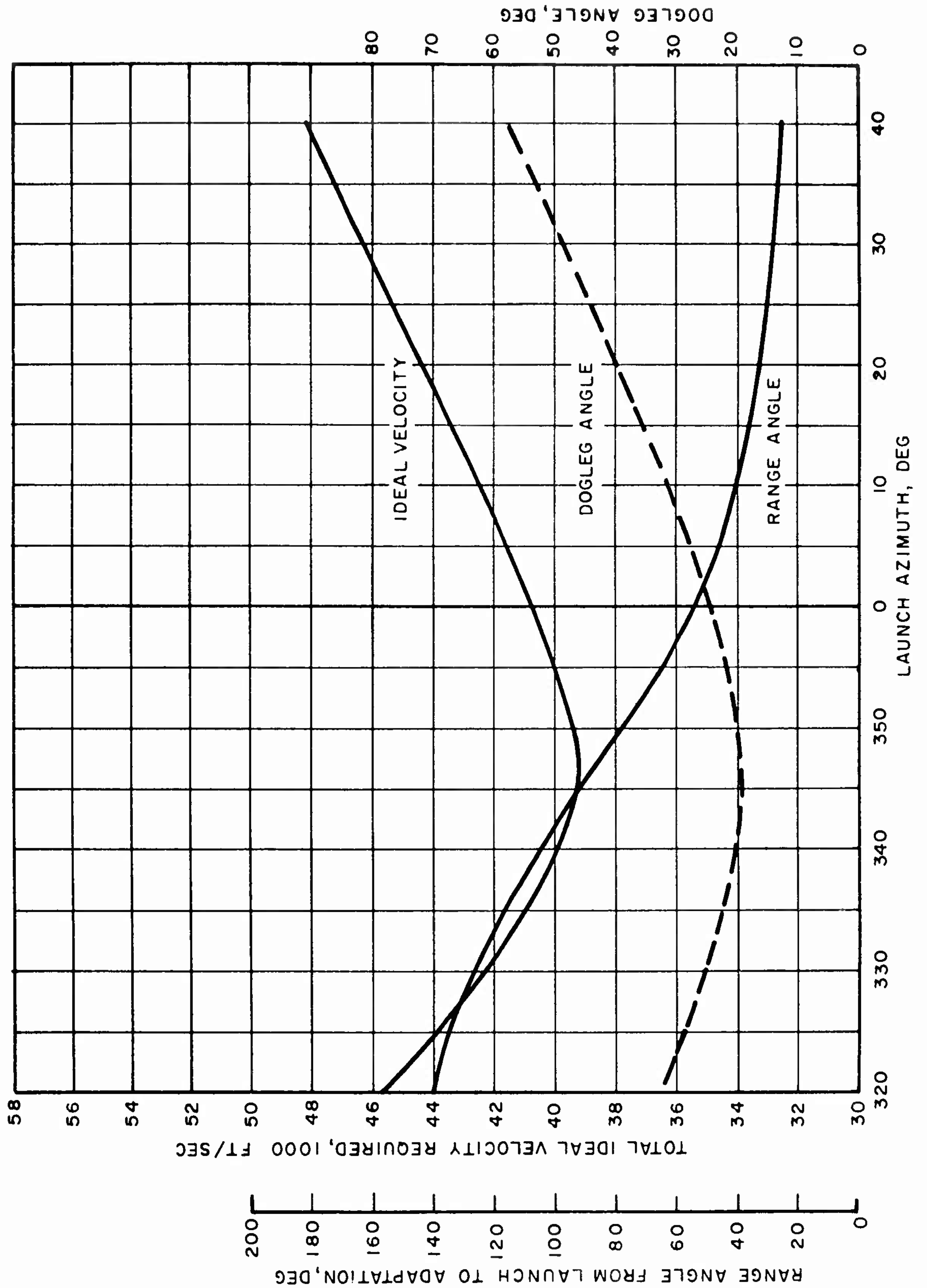


Figure 8. Performance with Relative Epoch = -1.068.

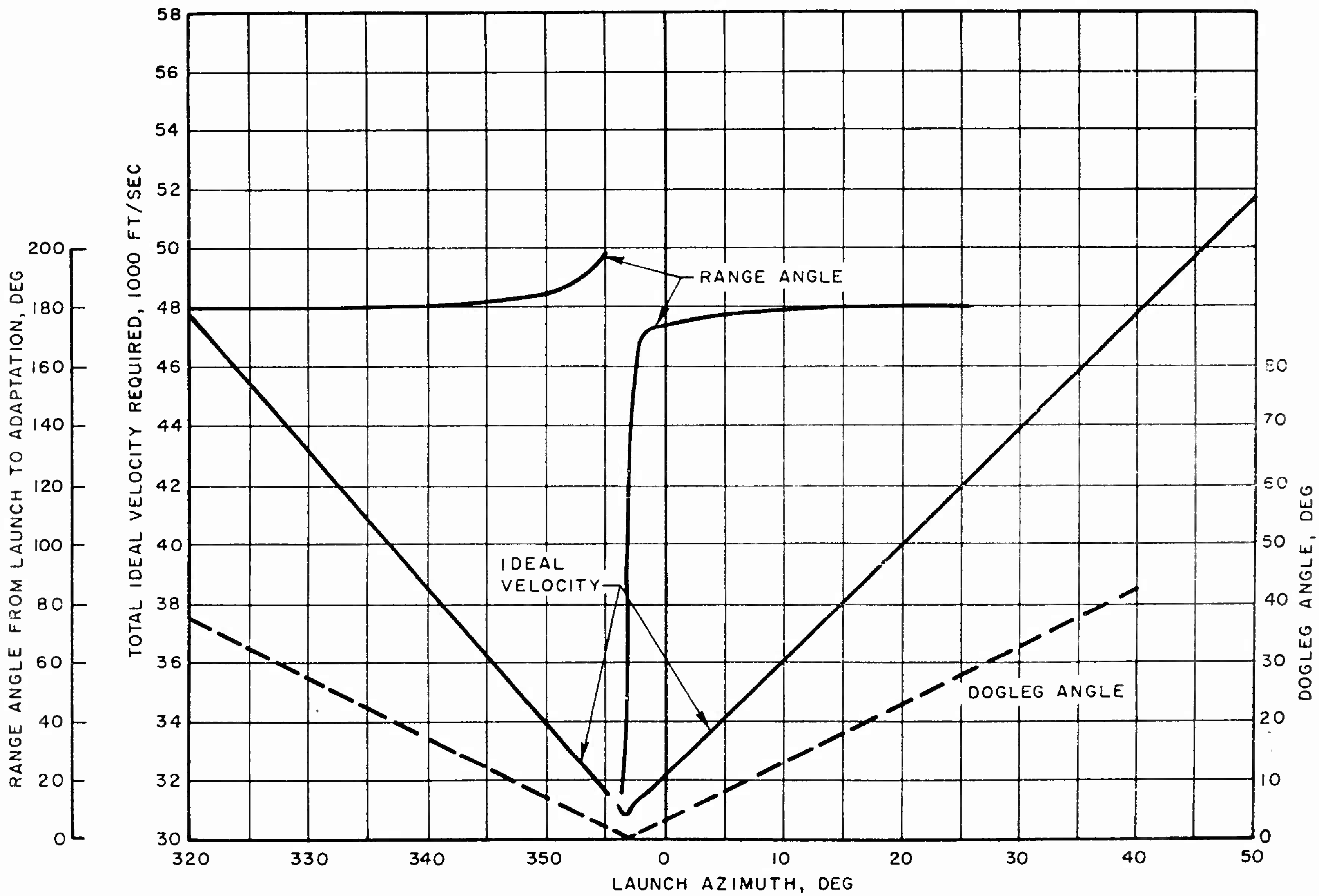
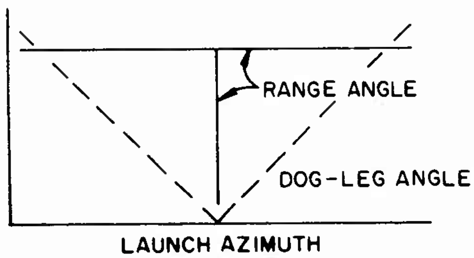


Figure 9. Performance with Relative Epoch = -0.068.

(in the discussion of Figures 3 and 4), with a low satellite altitude such as this, the launch time is a rather weak function of range angle; hence, for this particular relative epoch, the launch site is essentially in the plane of the orbit at launch regardless of launch azimuth or range angle. If this were precisely true (and if the ascent trajectory were truly planar), it would follow that either the ascent trajectory would lie in the orbit plane or the range angle would be 180 degrees. Further, the dog-leg angle would be equal to the difference between the selected launch azimuth and the in-plane launch azimuth. The curves of Figure 9 would then be straight lines as shown below.



The actual curves of Figure 9 show that the approximations above are quite reasonable for preliminary design purposes at this orbit altitude. However, one would expect the relationship between launch time and range angle to become stronger and hence the approximation progressively worse, as the orbit altitude increases.

Figures 10 and 11 continue the results with data on this same satellite on the two subsequent passes.

Figures 12 and 13 present similar data on a satellite in the same orbit plane as the one considered above but 180 degrees away from it in position at a given time. The figures present data for launches approximately one-half period before and after, respectively, the time when the launch site passes through the orbit plane. This particular satellite is of interest because, in

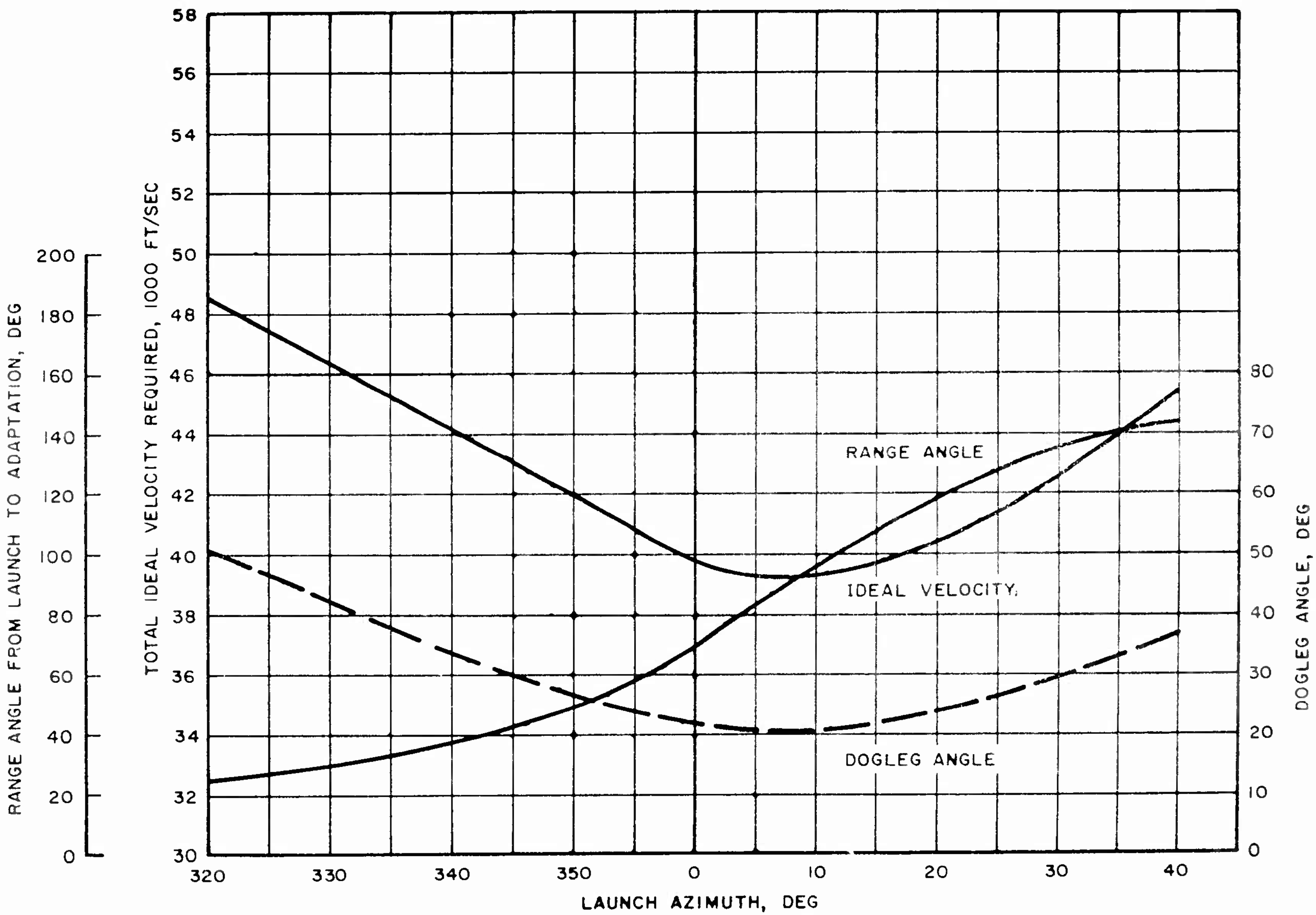


Figure 10. Performance with Relative Epoch = 0.932.

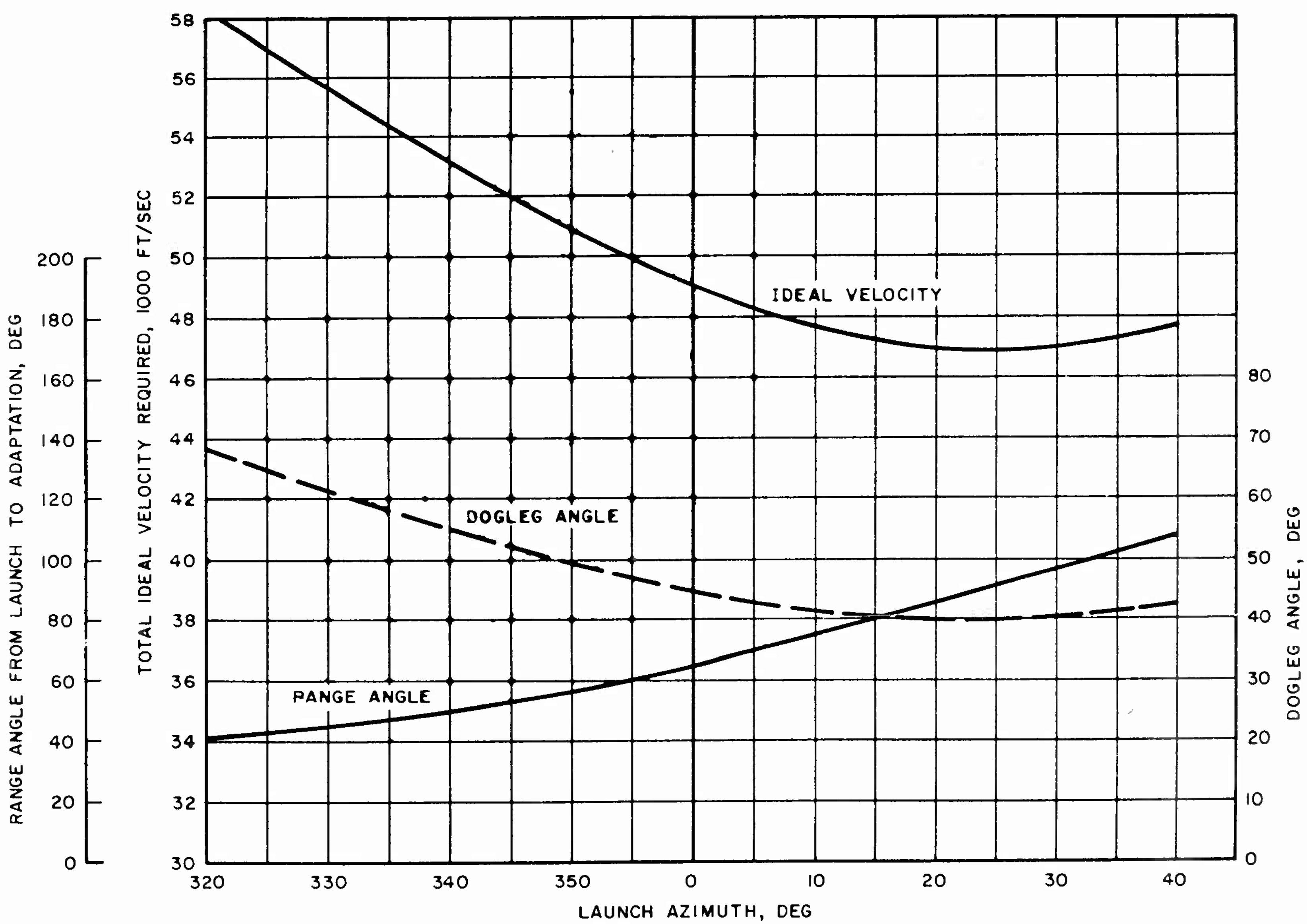


Figure 11. Performance with Relative Epoch = 1.932.

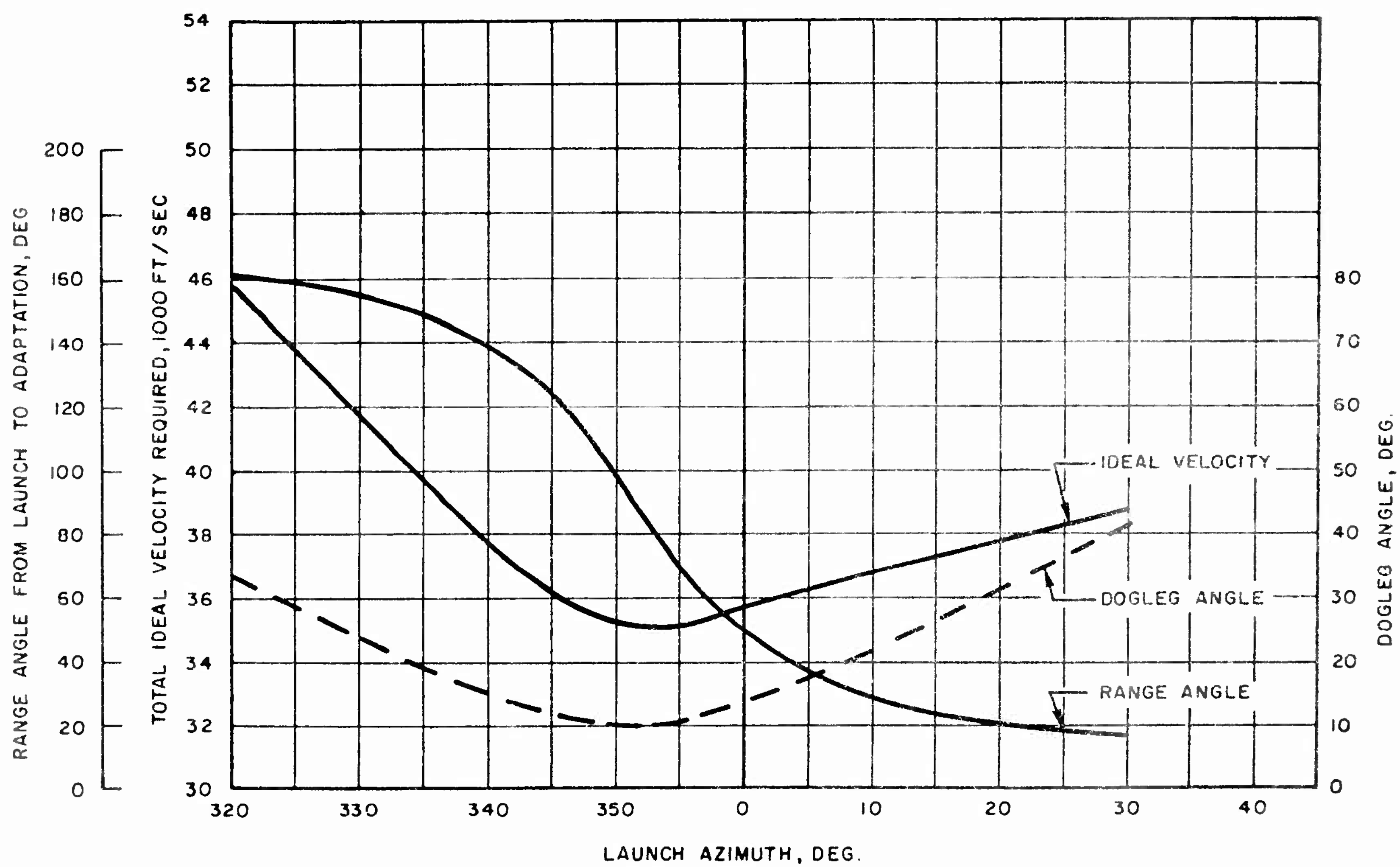


Figure 12. Performance with Relative Epoch = 0.568.

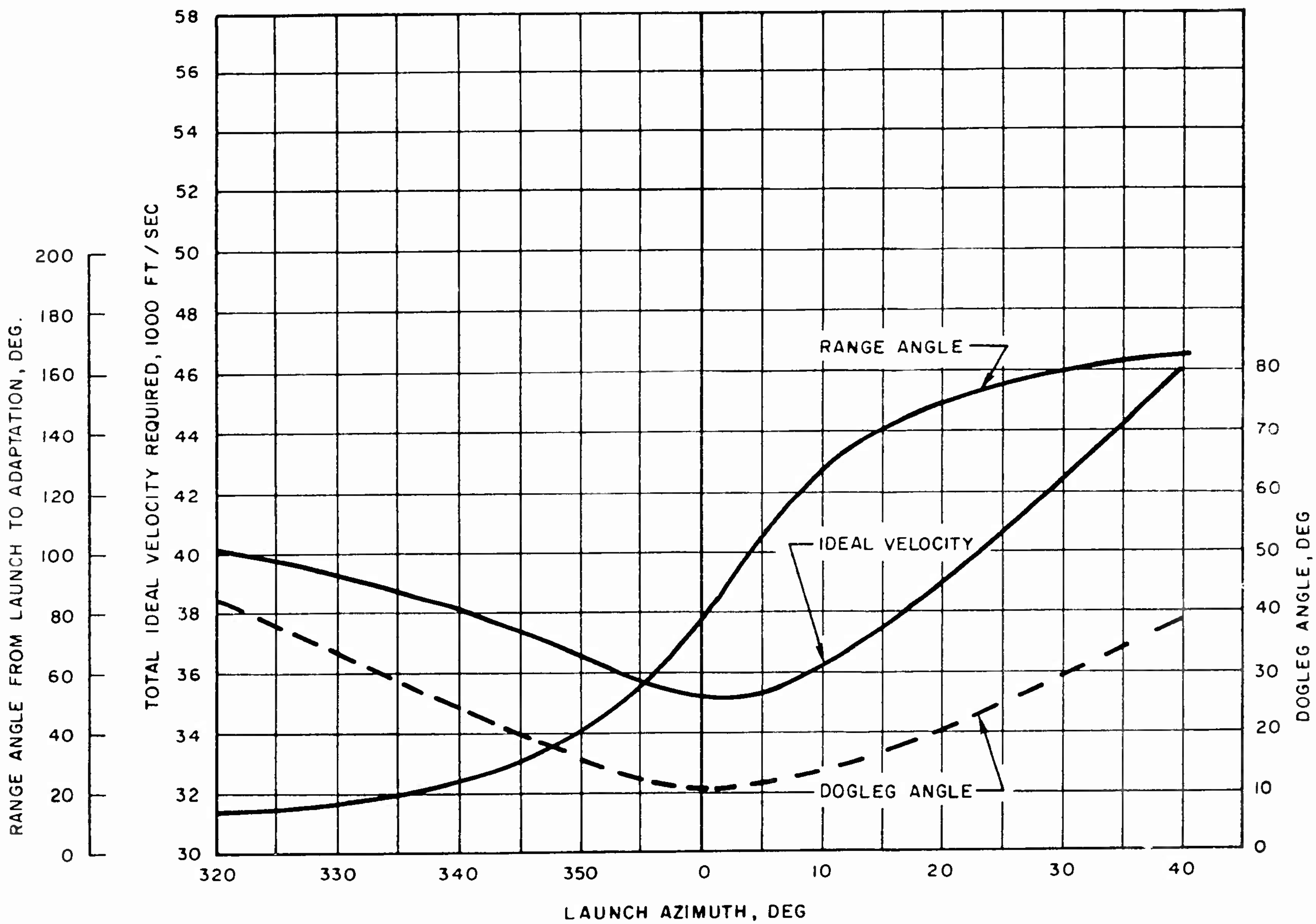


Figure 13. Performance with Relative Epoch = 0.432.

the absence of azimuth constraints, it is the most difficult to reach of the 200-nautical mile polar orbit satellites. The minimum ideal velocity required for rendezvous with this satellite is essentially the minimum required for 100 per cent coverage of 200-nautical mile polar orbits on a one-half day notice. These figures are seen to fall into the over-all pattern set by the previous figures. One again perceives a symmetry about the -0.068 relative epoch case. Careful comparison reveals that the -2.068 and +1.932 cases are almost mirror images of each other. The same is true of other similarly paired cases. This symmetry is due to the 90-degree inclination of the satellite orbit; as the inclination changes from 90 degrees the symmetry gradually disappears. The departures from symmetry with polar orbits are due to secondary earth rotation effects.

Figures 7 through 13 are of particular interest in that they display clearly the effect of launch azimuth on the range angle, dog-leg angle, and ideal velocity required. This effect is of importance for site selection and range safety reasons. In the in-plane-launch-possible case (Figure 9), the ideal velocity required is seen to be a sharp function of launch azimuth with even small departures from the optimum producing significant increases in required performance. Variation of the relative epoch in either direction, however, quickly flattens the curve. In most cases, launch azimuth can be varied by $\pm$ 5 degrees with little effect on the ideal velocity required.

Large changes in launch azimuth however have a major effect, driving the range angle to either very large or very small values, greatly increasing the ideal velocity required and often dictating the selection of a different pass as optimum. This is illustrated in Table 1 which lists the optimum trajectory characteristics for rendezvous with the satellite of Figures 7 through 11, both with and without AMR launch azimuth constraints. Without constraints, the optimum is an in-plane launch; azimuth $\cong$ 357 degrees, range angle $\cong$ 82 degrees, ideal velocity required = 30,800 ft/sec. With launch azimuth constraints, the

Table 1. Typical Effect of Launch Azimuth Constraints on Rendezvous with a Particular Satellite.*

	Unconstrained Optimum			Optimum with 40-Degree Azimuth Constraint		
Pass	Range Angle	Launch Azimuth	Ideal Velocity Required	Range Angle	Launch Azimuth	Ideal Velocity Required
-2	85	335	47, 500	43	40	58, 000
-1	85	348	39, 300	25	40	48, 100
0	82	357	30, 800	180	40	47, 700
1	90	8	39, 200	144	40	45, 300
2	90	23	46, 900	108	40	47, 800

*Relative epoch = 2.068, -1.068, -0.068, +0.932, +1.932
Altitude = 200 nautical miles
Inclination = 90 degrees
Rendezvous vehicle launched from AMR

optimum is to launch one pass later along the 40-degree azimuth constraint with a range angle of 144 degrees and a required ideal velocity of 45, 300 ft/sec.

III. CONCLUSIONS

This study has verified that, in the absence of launch azimuth constraints, the optimum flight plan from the launch vehicle performance viewpoint is to launch within a half period (approximately) of the time when the launch site passes through the orbit plane at a time and on a launch azimuth such that the rendezvous vehicle traverses an inertial range angle of about 90 degrees between launch and adaptation. Given freedom to follow this procedure, and to wait up to 24 hours for favorable launch conditions, a vehicle with an ideal velocity capability of 33, 000 ft/sec can achieve gross rendezvous with any satellite in a 200-nautical mile polar orbit (provided the velocity losses during ascent are not greater than those of an Atlas Agena).

If the presence of launch azimuth constraints requires only a small change in launch azimuth (up to $\pm$ 5 degrees) the optimum range angle will change perceptibly and will become a strong function of the relative epoch. A range angle of 180 degrees will be required for at least one particular epoch. The ideal velocity required for full coverage will be increased by perhaps 500 ft/sec.

If the presence of launch azimuth constraints forces large changes in launch azimuth, the following major effects will occur:

1. Optimum range angles will vary from very short (perhaps 20 degrees) to quite long (up to 180 degrees) depending on the constraints and the relative epoch.
2. The optimum launch time may be one or two passes earlier or later than in the unconstrained cases.
3. The total ideal velocity required will be greatly increased; application of AMR limits to polar orbits increases the ideal velocity required to 46, 000 ft/sec; roughly the amount needed for a probe of Mars or Venus.

The final result of the study is that enough was learned about direct ascent rendezvous to permit the programming of an approximate rendezvous performance analysis technique which will provide rapid mapping of the entire performance surface any time this is deemed desirable. The general basis of the technique is described in Reference 4; the mathematical formulation was altered during the programming. The program is now in operation.

REFERENCES

1. Martin, D. C., "System 621A Performance Parameters", Aerospace Corporation, TOR-390(2112)-4, 15 December 1961.

2. Coates, G. L., "Development of a Computer Program for Determining the Launch Vehicle Performance Required for Rendezvous or Satellite Intercept Missions", Aerospace Corporation, A62-1742.6-9, 1 November 1962.

3. "SAINT Phase II System Study", Space Technology Laboratories, Inc., TR59-0000-09913, 31 December 1959.

4. Coates, G. L., "Programming of an Approximate Rendezvous/Intercept Performance Analysis Technique", Aerospace Corporation, A62-1842.6-11, 26 December 1962.

UNCLASSIFIED

Aerospace Corporation, El Segundo, California. LAUNCH VEHICLE PERFORMANCE REQUIREMENTS FOR RENDEZVOUS WITH SATELLITES IN 200-NAUTICAL MILE CIRCULAR POLAR ORBITS, by G. L. Coates, 20 September 1963, 35 pages including illustrations. (Report No. TDR-169(3511)TN-5, SSD-TDR-63-233) (Contract No. AF04(695)-169). Unclassified Report

This report presents a detailed analysis of direct ascent rendezvous with polar orbits, illustrating quantitatively the effects of range angle, launch azimuth, and satellite epoch on the ascent trajectory and the performance required of the launch vehicle.

The total ideal velocity capability required of the launch vehicle to achieve gross rendezvous with satellites in 200-nautical mile circular polar

(over)

UNCLASSIFIED

UNCLASSIFIED

Aerospace Corporation, El Segundo, California. LAUNCH VEHICLE PERFORMANCE REQUIREMENTS FOR RENDEZVOUS WITH SATELLITES IN 200-NAUTICAL MILE CIRCULAR POLAR ORBITS, by G. L. Coates, 20 September 1963. 35 pages including illustrations. (Report No. TDR-169(3511)TN-5, SSD-TDR-63-233) (Contract No. AF04(695)-169). Unclassified Report

This report presents a detailed analysis of direct ascent rendezvous with polar orbits, illustrating quantitatively the effects of range angle, launch azimuth, and satellite epoch on the ascent trajectory and the performance required of the launch vehicle.

The total ideal velocity capability required of the launch vehicle to achieve gross rendezvous with satellites in 200-nautical mile circular polar

(over)

UNCLASSIFIED

UNCLASSIFIED

Aerospace Corporation, El Segundo, California. LAUNCH VEHICLE PERFORMANCE REQUIREMENTS FOR RENDEZVOUS WITH SATELLITES IN 200-NAUTICAL MILE CIRCULAR POLAR ORBITS, by G. L. Coates, 20 September 1963, 35 pages including illustrations. (Report No. TDR-169(3511)TN-5, SSD-TDR-63-233) (Contract No. AF04(695)-169). Unclassified Report

This report presents a detailed analysis of direct ascent rendezvous with polar orbits, illustrating quantitatively the effects of range angle, launch azimuth, and satellite epoch on the ascent trajectory and the performance required of the launch vehicle.

The total ideal velocity capability required of the launch vehicle to achieve gross rendezvous with satellites in 200-nautical mile circular polar

(over)

UNCLASSIFIED

UNCLASSIFIED

Aerospace Corporation, El Segundo, California. LAUNCH VEHICLE PERFORMANCE REQUIREMENTS FOR RENDEZVOUS WITH SATELLITES IN 200-NAUTICAL MILE CIRCULAR POLAR ORBITS, by G. L. Coates, 20 September 1963, 35 pages including illustrations. (Report No. TDR-169(3511)TN-5, SSD-TDR-63-233) (Contract No. AF04(695)-169). Unclassified Report

This report presents a detailed analysis of direct ascent rendezvous with polar orbits, illustrating quantitatively the effects of range angle, launch azimuth, and satellite epoch on the ascent trajectory and the performance required of the launch vehicle.

The total ideal velocity capability required of the launch vehicle to achieve gross rendezvous with satellites in 200-nautical mile circular polar

(over)

UNCLASSIFIED

UNCLASSIFIED

orbits was determined as a function of the launch azimuth, the relative epoch of the orbit, and the pass on which rendezvous takes place. A direct ascent launch vehicle trajectory was assumed. Precision flight simulation techniques were used throughout except for the assumption of an impulsive adaptation maneuver. Launch window effects were not included; rather, the study was concerned with the selection and characteristics of nominal trajectories.

UNCLASSIFIED

UNCLASSIFIED

orbits was determined as a function of the launch azimuth, the relative epoch of the orbit, and the pass on which rendezvous takes place. A direct ascent launch vehicle trajectory was assumed. Precision flight simulation techniques were used throughout except for the assumption of an impulsive adaptation maneuver. Launch window effects were not included; rather, the study was concerned with the selection and characteristics of nominal trajectories.

UNCLASSIFIED

UNCLASSIFIED

orbits was determined as a function of the launch azimuth, the relative epoch of the orbit, and the pass on which rendezvous takes place. A direct ascent launch vehicle trajectory was assumed. Precision flight simulation techniques were used throughout except for the assumption of an impulsive adaptation maneuver. Launch window effects were not included; rather, the study was concerned with the selection and characteristics of nominal trajectories.

UNCLASSIFIED

UNCLASSIFIED

orbits was determined as a function of the launch azimuth, the relative epoch of the orbit, and the pass on which rendezvous takes place. A direct ascent launch vehicle trajectory was assumed. Precision flight simulation techniques were used throughout except for the assumption of an impulsive adaptation maneuver. Launch window effects were not included; rather, the study was concerned with the selection and characteristics of nominal trajectories.

UNCLASSIFIED

UNCLASSIFIED

Aerospace Corporation, El Segundo, California. LAUNCH VEHICLE PERFORMANCE REQUIREMENTS FOR RENDEZVOUS WITH SATELLITES IN 200-NAUTICAL MILE CIRCULAR POLAR ORBITS, by G. L. Coates, 20 September 1963. 35 pages including illustrations. (Report No. TDR-169(3511)TN-5, SSD-TDR-63-233) (Contract No. AF04(695)-169). Unclassified Report

This report presents a detailed analysis of direct ascent rendezvous with polar orbits, illustrating quantitatively the effects of range angle, launch azimuth, and satellite epoch on the ascent trajectory and the performance required of the launch vehicle.

The total ideal velocity capability required of the launch vehicle to achieve gross rendezvous with satellites in 200-nautical mile circular polar

(over)

UNCLASSIFIED

UNCLASSIFIED

Aerospace Corporation, El Segundo, California. LAUNCH VEHICLE PERFORMANCE REQUIREMENTS FOR RENDEZVOUS WITH SATELLITES IN 200-NAUTICAL MILE CIRCULAR POLAR ORBITS, by G. L. Coates, 20 September 1963. 35 pages including illustrations. (Report No. TDR-169(3511)TN-5, SSD-TDR-63-233) (Contract No. AF04(695)-169). Unclassified Report

This report presents a detailed analysis of direct ascent rendezvous with polar orbits, illustrating quantitatively the effects of range angle, launch azimuth, and satellite epoch on the ascent trajectory and the performance required of the launch vehicle.

The total ideal velocity capability required of the launch vehicle to achieve gross rendezvous with satellites in 200-nautical mile circular polar

(over)

UNCLASSIFIED

UNCLASSIFIED

Aerospace Corporation, El Segundo, California. LAUNCH VEHICLE PERFORMANCE REQUIREMENTS FOR RENDEZVOUS WITH SATELLITES IN 200-NAUTICAL MILE CIRCULAR POLAR ORBITS, by G. L. Coates, 20 September 1963, 35 pages including illustrations. (Report No. TDR-169(3511)TN-5, SSD-TDR-63-233) (Contract No. AF04(695)-169). Unclassified Report

This report presents a detailed analysis of direct ascent rendezvous with polar orbits, illustrating quantitatively the effects of range angle, launch azimuth, and satellite epoch on the ascent trajectory and the performance required of the launch vehicle.

The total ideal velocity capability required of the launch vehicle to achieve gross rendezvous with satellites in 200-nautical mile circular polar

(over)

UNCLASSIFIED

UNCLASSIFIED

Aerospace Corporation, El Segundo, California. LAUNCH VEHICLE PERFORMANCE REQUIREMENTS FOR RENDEZVOUS WITH SATELLITES IN 200-NAUTICAL MILE CIRCULAR POLAR ORBITS, by G. L. Coates, 20 September 1963, 35 pages including illustrations. (Report No. TDR-169(3511)TN-5, SSD-TDR-63-233) (Contract No. AF04(695)-169). Unclassified Report

This report presents a detailed analysis of direct ascent rendezvous with polar orbits, illustrating quantitatively the effects of range angle, launch azimuth, and satellite epoch on the ascent trajectory and the performance required of the launch vehicle.

The total ideal velocity capability required of the launch vehicle to achieve gross rendezvous with satellites in 200-nautical mile circular polar

(over)

UNCLASSIFIED

orbits was determined as a function of the launch azimuth, the relative epoch of the orbit, and the pass on which rendezvous takes place. A direct ascent launch vehicle trajectory was assumed. Precision flight simulation techniques were used throughout except for the assumption of an impulsive adaptation maneuver. Launch window effects were not included; rather, the study was concerned with the selection and characteristics of nominal trajectories.

UNCLASSIFIED

UNCLASSIFIED

orbits was determined as a function of the launch azimuth, the relative epoch of the orbit, and the pass on which rendezvous takes place. A direct ascent launch vehicle trajectory was assumed. Precision flight simulation techniques were used throughout except for the assumption of an impulsive adaptation maneuver. Launch window effects were not included; rather, the study was concerned with the selection and characteristics of nominal trajectories.

UNCLASSIFIED

UNCLASSIFIED

orbits was determined as a function of the launch azimuth, the relative epoch of the orbit, and the pass on which rendezvous takes place. A direct ascent launch vehicle trajectory was assumed. Precision flight simulation techniques were used throughout except for the assumption of an impulsive adaptation maneuver. Launch window effects were not included; rather, the study was concerned with the selection and characteristics of nominal trajectories.

UNCLASSIFIED

UNCLASSIFIED

orbits was determined as a function of the launch azimuth, the relative epoch of the orbit, and the pass on which rendezvous takes place. A direct ascent launch vehicle trajectory was assumed. Precision flight simulation techniques were used throughout except for the assumption of an impulsive adaptation maneuver. Launch window effects were not included; rather, the study was concerned with the selection and characteristics of nominal trajectories.

UNCLASSIFIED

UNCLASSIFIED